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SPECTROPHOTOMETRIC EXPERIMENT ON THE "VENERA-11" AND "VENERA-12"  
DESCENT VEHICLES: SOME RESULTS OF THE ANALYSIS OF THE SPECTRUM OF  
THE DAYTIME SKY OF VENUS

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Synopsis

Recorded on the descent vehicles "Venera-11" and "Venera-12", in the course of re-entry in the atmosphere (from an altitude of 65 km to the surface), were the spectra of the daytime sky of Venus at an interval of from 4500 to 12,000 Å, and the angular distribution of the brightness of the scattered radiation (in four filters). Visible on the spectra were zones of absorption of CO<sub>2</sub>, H<sub>2</sub>O, and slight absorption in the blue-green portion of the spectrum, which probably belongs to gaseous sulfur. The abundance of [H<sub>2</sub>O]:[CO<sub>2</sub>]  $\approx 2 \cdot 10^{-9}$  is in the area of the lower scale of altitudes. If the identification with sulfur is correct, then its abundance is about  $10^{-8}$  in this same area. About 6% of the total solar flow reaches the surface of the planet. The lower boundary of the clouds is located at an altitude of about 47-48 km, and the clouds have a Stratus structure.

Solar radiation penetrates into the deep layers of the atmosphere of Venus, in spite of its great optical thickness. It is scattered repeatedly in the cloud cover and the atmosphere below the clouds, and direct solar radiation is impossible to detect in the depth of the atmosphere; however, the scattered radiation may be quite intense in some sections of the spectrum. An appreciable portion of the flow reaches the surface, and, as a result, because of the great nontransparency

/1\*

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of the atmosphere for thermal radiation, a strong hothouse effect occurs, which explains the high temperature of the surface.

The task of the described experiment is the measurement of the spectral and angular distribution of the energy of the scattered radiation, as a function of the altitude, using an instrument mounted on the descent vehicle. Interpretation of the results of the experiment makes it possible to solve problems of three types: 1) determination of the radiation influx of energy as a function of the altitude, which is necessary for understanding of the thermal balance and the dynamics of the atmosphere; 2) determination of the structure of the cloud cover; 3) ascertaining of the chemical nature of the different absorbing agents present in the atmosphere of Venus in the gas and aerosol phase.

The first experiment for measuring the radiation flow in the deep layers of the atmosphere of Venus was carried out on "Venera-8" in 1972 (Avduevskiy et al., 1973). The flow from above was measured in a zone about 2500 Å wide, centered at a wavelength of 6500 Å. Two different experiments on the investigation of the field of scattered radiation in the atmosphere were carried out in two different groups on the "Venera-9" and "Venera-10". In one of them (Avduevskiy et al., 1976, Ekonomov et al., 1978), flows from above and below were measured with five wide (on the order of a thousand Angstroms) filters, encompassing an interval from 0.5 to 1.2 microns. Carried out in the second experiment (Moroz et al., 1976) were measurements of the intensity of the radiation with three narrow (about 50 Å) filters, centered on zones of CO<sub>2</sub> and H<sub>2</sub>O, and a section of the uninterrupted spectrum, located in the 8000-9000 Å interval.

/2

During preparation of the new experiment on "Venera-11" and "Venera-12", the efforts and experience of both groups were joined, and, as a result, a new instrument was created, which possesses substantially new capabilities (fig. 1). The instrument consists of two functional units—a spectrometer and a scanning photometer. The radiation enters the spectrometer through a flexible light guide  $C_1$ , which accepts the radiation from the area of the zenith at an angle of about  $15^\circ$ . It then passes through a hermetic window  $O_1$ , a wedge-shaped interference filter KIF and a lens  $L_1$ , and is collected at the receiver  $P_1$  (a germanium photodiode). The circular wedge-shaped interference filter consists of two half-rings, one of which analyzes the range from 4500 to 7000 Å with resolution of about 200 Å, and the second—the range from 7000 to 8000 Å, with a resolution of about 400 Å. The external diameter of the filter is 50 mm. The disk with the wedge-shaped filter rotates with a cycle of 10 seconds, and it is set in motion by a motor D through a reduction gear. Mounted on the same disk as the wedge-shaped interference filter are 4 broad glass filters F, made up in the form of sectors of  $90^\circ$  each and pointing out broad spectral intervals, centered at 4900, ((PAGE MISSING AT THIS POINT)) .....

here, within a 10-20% range, do not differ (with the exception of the blue portion of the spectrum) from those which would be radiation reflected from the Lambertian screen, illuminated by the sun. Presented in figure 2 are several characteristic spectra, related to this conditional standard. The spectra are given schematically, without showing some weak details, the reality of which requires additional verification. The high-level surveying is preliminary.

4

The intensity of the radiation is weakened in proportion to the descent at all wavelengths, right up to an altitude

of 47-48 km, i.e., inside of the cloud cover. Also visible are weak, but fully-certain depressions, which are gradually intensified. These are bands of absorption of  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , and slight absorption in the blue portion of the spectrum.

After the passage of a level of 47-48 km, the changes in the spectrum (both according to absolute magnitude and according to distribution) cease. The spectra at an altitude of 38 and 48 km are practically identical. We explain this as the effect of crossing of the lower boundary of the cloud cover. The first 10 km of the atmosphere under its lower boundary almost never add to the measurable intensity. On "Venera-9" and "Venera-10", the lower boundary of the cloud cover was recorded (Avduevskiy et al., 1976; Marov et al., 1976; Moroz et al., 1976; Ekonomov et al., 1978) at a close altitude (49-50 km), but a somewhat weaker scattering environment was observed below the boundary.

Below 38 km to the surface, the depth of the  $\text{CO}_2$  and  $\text{H}_2\text{O}$  zones increases systematically. In addition, there is a severe "avalanche" in the blue-green region of the spectrum—stronger than that which may give a Rayleigh scattering. One can indicate several molecules, gaseous sulfur,  $\text{Br}_2$ , and  $\text{NO}_2$ , which, with a very low abundance ( $10^{-8}$ - $10^{-9}$ , with respect to  $\text{CO}_2$ ) may be responsible for this absorption.

It was decided to carry out analysis of the spectrum of passage of the atmosphere under the clouds as the first step during interpretation of the data obtained in the spectrophotometric experiment on "Venera-11" and "Venera-12". The measured dependence of the ratio of the intensities on the wavelength at altitudes of 0 and 47 km (surface of the planet and lower boundary of the cloud cover) was compared with that calculated for the following model: homogeneous  $\text{CO}_2$  layer with an admixture of a small amount of  $\text{H}_2\text{O}$  (variable para-

45

meter in the model), the pressure in the layer is equal to the pressure on the surface (91 atmospheres), and the thickness of the layer is equal to the altitude of the homogeneous atmosphere. The passage of such a layer, for a diffuse source, is equal to

$$\rho_T = \rho_0(\bar{\mu}, \mu_2, a, \tau_0) + \frac{AVF}{1-AW} + e^{-\tau} \left(1 + \frac{AV}{1-AW}\right), \quad (1)$$

where  $\bar{\mu}=0.7$  is the average value of the cosine of the angle of incidence,  $\mu_2=1$  is the cosine of the angle of sight (optical axis of the spectrophotometer is oriented towards the zenith).

$$a = \frac{\sigma}{\sigma + k} \quad (2)$$

is the albedo of a single scattering,

$$\sigma = 8.07 \cdot 10^{-4} \lambda^{-4} \text{ cm}^{-1} \quad (3)$$

is the coefficient of Rayleigh scattering for  $\text{CO}_2$  ( $\lambda$  is the wave length, in microns);  $k$  is the total coefficient of absorption ( $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{S}_2$ — $\text{S}_g$ ), etc.;  $\tau$  is the optical thickness;  $\rho_0(\bar{\mu}, \mu_2, a, \tau)$  is the coefficient of brightness for the scattered radiation;  $e^{-\tau}$  is the coefficient of brightness for the direct radiation weakened by extinction;  $A$  is the albedo of the surface. The optical thickness of the layer  $\tau_0$  for the Rayleigh scattering varies within the range from roughly 0.8 ( $\lambda=12,000 \text{ \AA}$ ) to 40 ( $\lambda=4500 \text{ \AA}$ ). The terms which include  $AV/(1-AW)$  take into account the re-reflection between the surface and the gas layer. The corresponding auxiliary functions  $V$ ,  $W$ , and  $F$  were calculated according to the asymptotic formulas of the theory of scattering, given in the study of Danielson et al. (1969). The magnitudes of

$\mathcal{P}_0(\bar{\mu}, \mu_2, a, \gamma_0)$  were calculated by two methods: first was the calculation according to the strict formulas of the theory of multiple scattering of light, using the auxiliary functions of Chandrasekar for the Rayleigh indicatrix  $\mathcal{X}(\gamma) = 3/4 (1 + \cos^2 \gamma)$ , and the second—calculation according to the asymptotic formulas of Danielson et al. (1969), assuming a spherical indicatrix. Both methods give identical results with  $a > 0.95$  and  $\gamma > 4$ . With lesser values of  $\gamma$  and  $a$ , we utilized the  $\mathcal{P}_0$  obtained by the first method, and the second method was used chiefly for extrapolation into the region of larger  $\gamma$ , for which there are no tabular data according to the X,Y-functions (used here were the tables of Sweigart, 1970).

The coefficients of absorption of  $\text{CO}_2$  were taken according to the data of Gal'tsev and Osipov (calculations which lay at the basis of the study of Gal'tsev et al., 1976). For the coefficients of absorption of  $\text{H}_2\text{O}$ , we did not find the data in the literature necessary for the model ( $\lambda < 1.2$  microns, measurements under conditions of a temperature of  $700\text{--}750^\circ\text{K}$  and high pressures). We measured these coefficients of absorption in the laboratory, using a high-temperature absorption cuvette 1 m long, with an  $\text{H}_2\text{O}$  content of  $3\text{ g}\cdot\text{cm}^{-2}$ , on a line of sight with spectral resolution of from 4 to 8 Å. The pressure in the cuvette was about 12 atmospheres, which, according to the conditions of expansion of the lines, satisfactorily simulate the conditions in the lower atmosphere of Venus (coefficient of self-expansion of  $\text{H}_2\text{O}$  of about 4 with respect to  $\text{CO}_2$ , and the line widths in our cuvette should be the same as those in the atmosphere of Venus at an altitude of 10 km). The rotational structure of the  $\text{H}_2\text{O}$  zones in the lower levels of the atmosphere of Venus should be severely obliterated, and is practically absent in the  $\text{CO}_2$  zones.

Comparison of the measurements with the model calculations

27

(carried out with averaging of 50 Å) showed that, within the limits of the lower scale of altitudes of the atmosphere of Venus

$$[H_2O]:[CO_2] \approx 2 \cdot 10^{-5} \quad (4)$$

The slight indeterminateness is associated with the disregarding of the rotational structure of the  $H_2O$  and the inaccuracies in the utilized values of the coefficients of continual absorption of  $CO_2$ , brought about by the sides of the far zones, but we are convinced that the given evaluation does not differ from the true abundance of  $H_2O$  by more than 2 times. This result does not coincide with the results of measurements on "Pioneer-Venus" (Oyama et al., 1979), according to which there is 0.5%  $H_2O$  at an altitude of 34 km, and 0.135% at an altitude of 24 km. It is safe to say that, with a 0.1-0.5% content of  $H_2O$ , the spectrum of the atmosphere under the clouds would be of an entirely different form. According to preliminary evaluations, obtained on the basis of our spectra, the content of  $H_2O$  in the atmosphere of Venus, at any altitudes, does not exceed levels on the order of  $10^{-4}$ .

The absorption in the range  $\lambda < 6000$  Å, using the very same model, is explained most satisfactorily by the absorption of gaseous sulfur, although the contribution of other molecules ( $Br_2$ ,  $NO_2$ ) cannot be excluded. The weakly-pronounced, but probably actual structure of the measured spectrum, which is available in this range, matches that of sulfur. We carried out laboratory measurements of the absorption of gaseous sulfur at temperatures of 600-800° K, which show similar details. If this identification is correct, then the relative abundance is

$$\frac{[S_2] + [S_4] + [S_6] + [S_8]}{[CO_2]} \approx 10^{-8} \quad (5)$$

We would note that, at the indicated temperatures, all of the enumerated modifications of sulfur are present. Such low evaluations for gaseous sulfur in the atmosphere under the clouds probably create difficulties for the hypotheses, which explain the "ultraviolet" absorption in the clouds by the presence there of condensed sulfur (Young, 1977). If one is diverted from the mentioned weak details in the measured spectrum, then the "blue avalanche" may be explained also by the presence of bromine molecules with a relative abundance of a total of  $10^{-10}$ , and of  $\text{NO}_2$  (roughly  $5 \cdot 10^{-10}$ ). In any case, the indicated abundances of sulfur, bromine, and  $\text{NO}_2$  may be viewed as the upper limits. In the range from 6000 to roughly 7000 Å, the albedo of one-time scattering in the lower atmosphere of Venus is located in the range from 0.999 to 1.000. In this section, about 10% of the sunlight reaches the surface. The portion of the total (integrated according to the spectrum) sunlight reaching the surface is about 6%.

/8

Given schematically in figure 3 is the dependence of the intensity at the zenith (for several wavelengths) on the altitude, also according to the data of the spectrometer. Points in the cloud cover are added. Evident in addition to the sharp lower boundary of the clouds are intermediate boundaries, which evidently reflect their complex vertical structure: they are subdivided into at least three layers. The presence of a somewhat vertical structure in the clouds was noted earlier in the experiments on "Venera-9" and "Venera-10" (Avduevskiy et al., 1976; Marov et al., 1976; Moroz et al., 1976). Analysis of the data on the characteristics of the cloud cover, obtained in the current experiment, will be given in subsequent reports.

The preliminary results given here demonstrate the special capabilities of the spectroscopic procedure as applied to the chemical analysis of the lower atmosphere of Venus.

Even with resolution of 200-300 Å, it proves possible, according to some components, to obtain sensitivities on the order of  $10^{-9}$ , which are unattainable for on-board mass-spectrometers and gas chromatographs. An increase in the resolution by an order considerably expands these capabilities.

The contradiction in the ratio of  $H_2O$  is not limited to the discrepancies between the American chromatograph and our spectrophotometer. Obtained on "Venera-4", "Venera-5", and "Venera-6" (Vinogradov et al., 1970), using chemical gas analyzers, was up to 2%  $H_2O$ . These results seem doubtful, but the possibility of strong local variations is not precluded. Further investigations are necessary, utilizing some standard and absolutely reliable procedure; with the utilization of direct chemical analyses, as the available experience shows, spectrophotometric monitoring will be very useful.

/9

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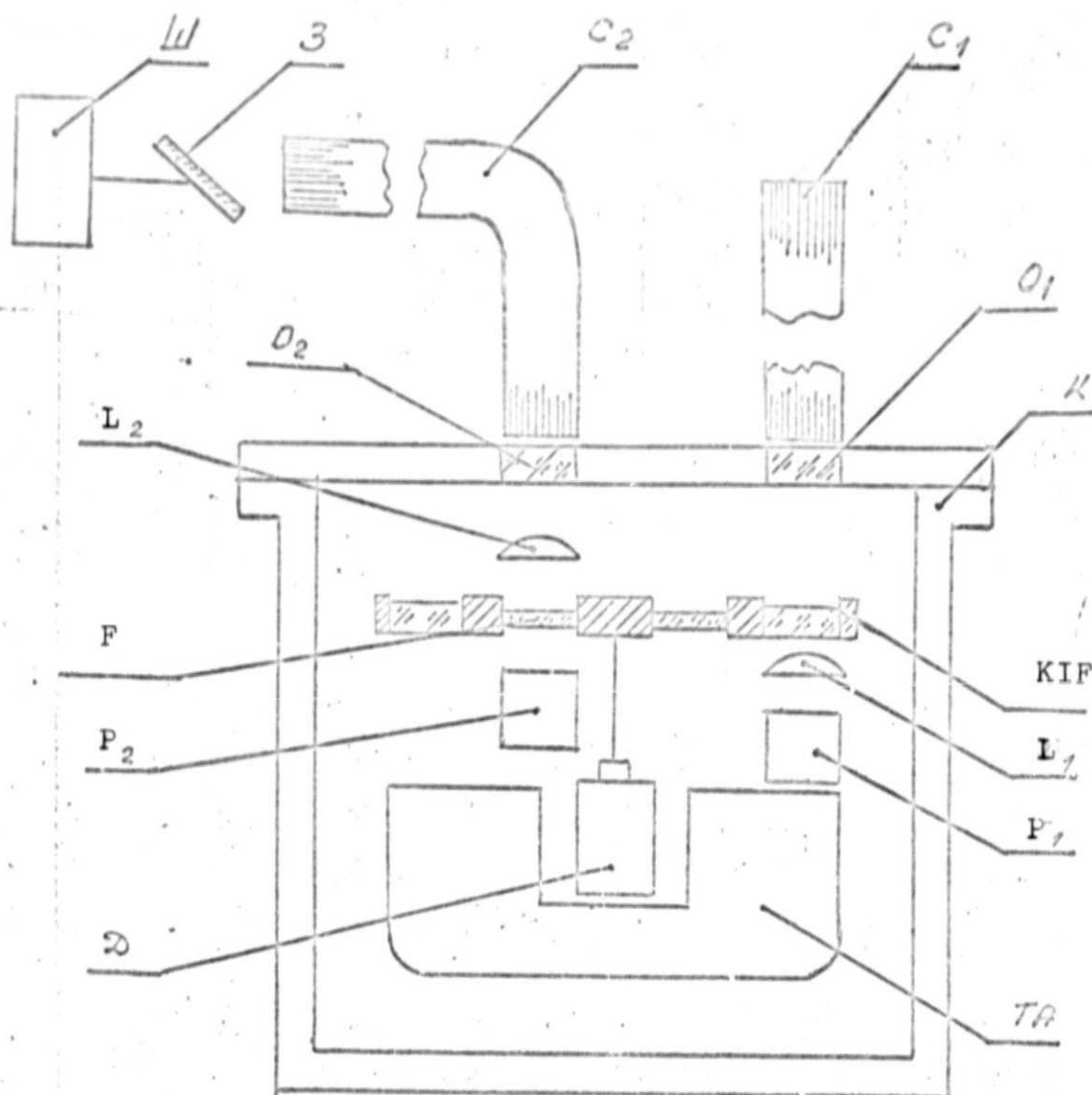
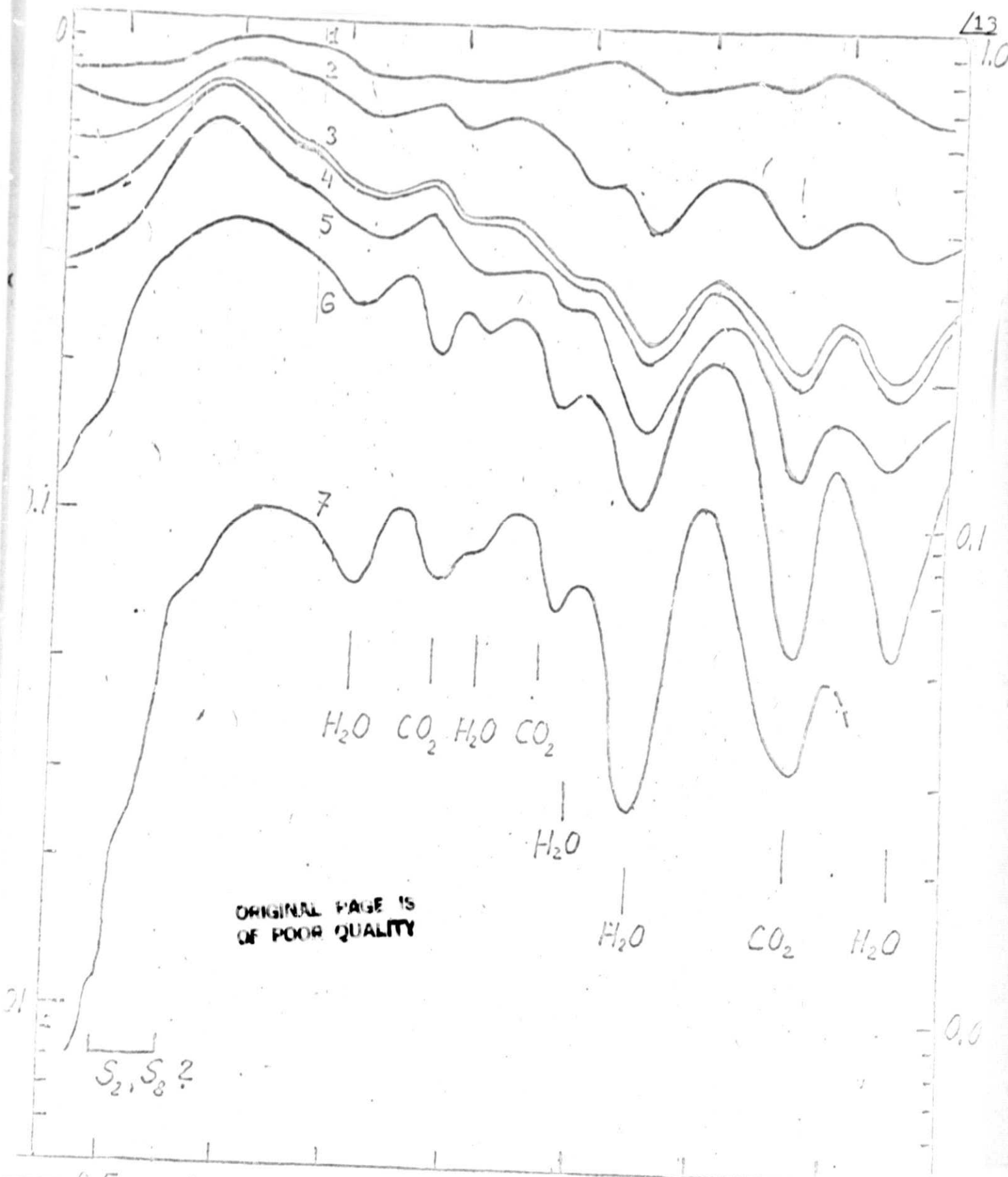
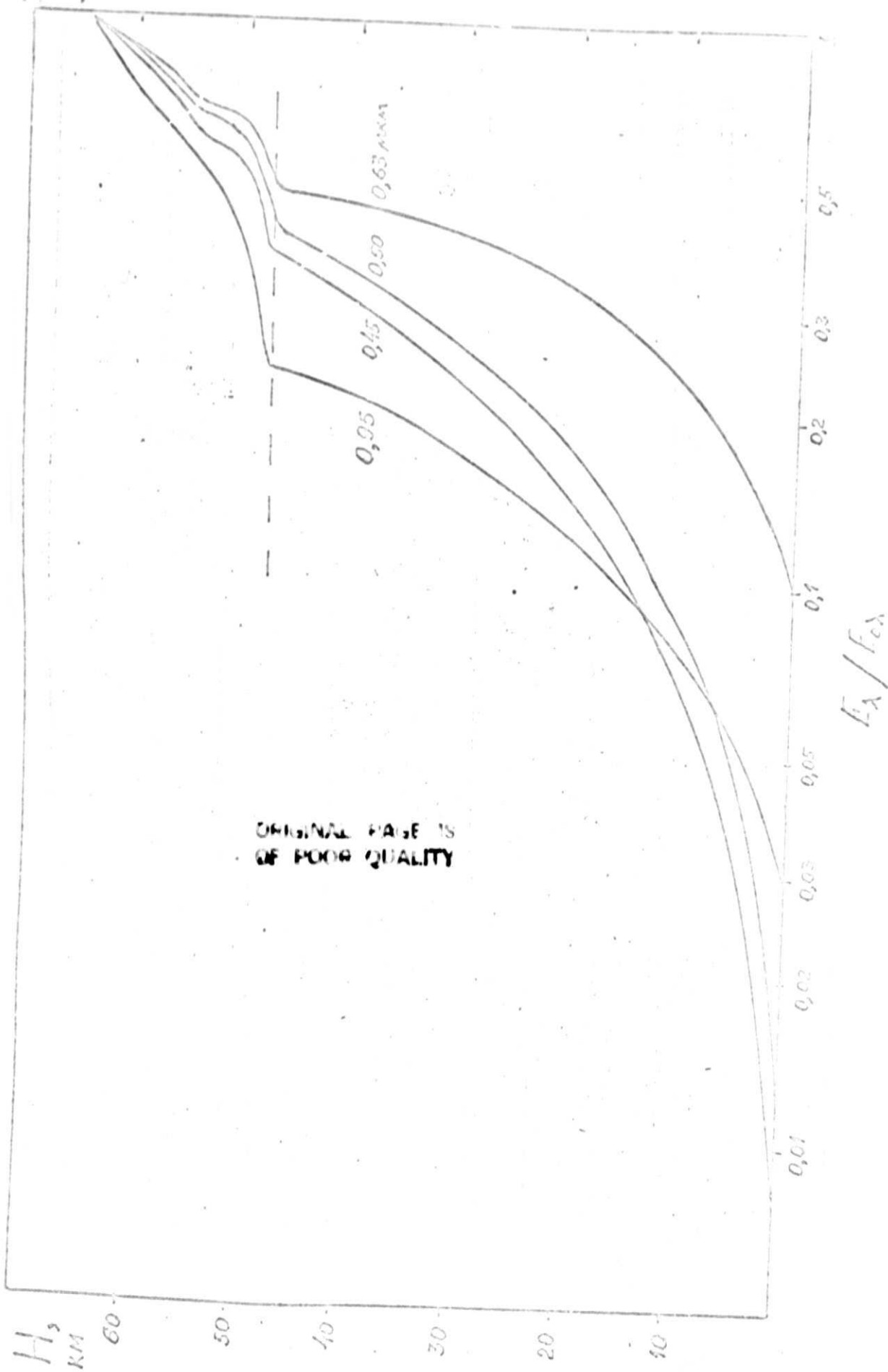


Fig. 1  
Diagram of optical-mechanical block (guage) of spectrophotometer.

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Fig. 2. Normed spectra of scattered solar radiation in the depth of the atmosphere of Venus at different altitudes above the surface. Along the x-axis are the wavelengths, and along the y-axis—the relative intensity (taken as the standard for norming are the spectra at altitudes of 63-65 km, see text). The numbers near the curves are the altitude above the surface: 1—56 km, 2—50 km, 3—47 km, 4—38 km, 5—27 km, 6—14 km, 7—0 km.





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Fig. 3.  
Normed intensity, as a function of altitude, for several wavelengths.  
The dotted line indicated the lower boundary of the cloud cover.